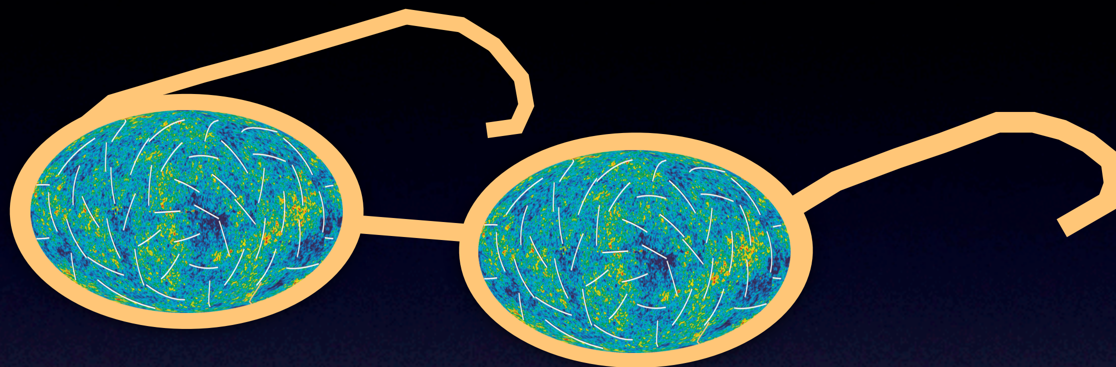
Fundamental Physics



Brian Keating

9 September 2013 TAUP

http://cosmology.ucsd.edu/

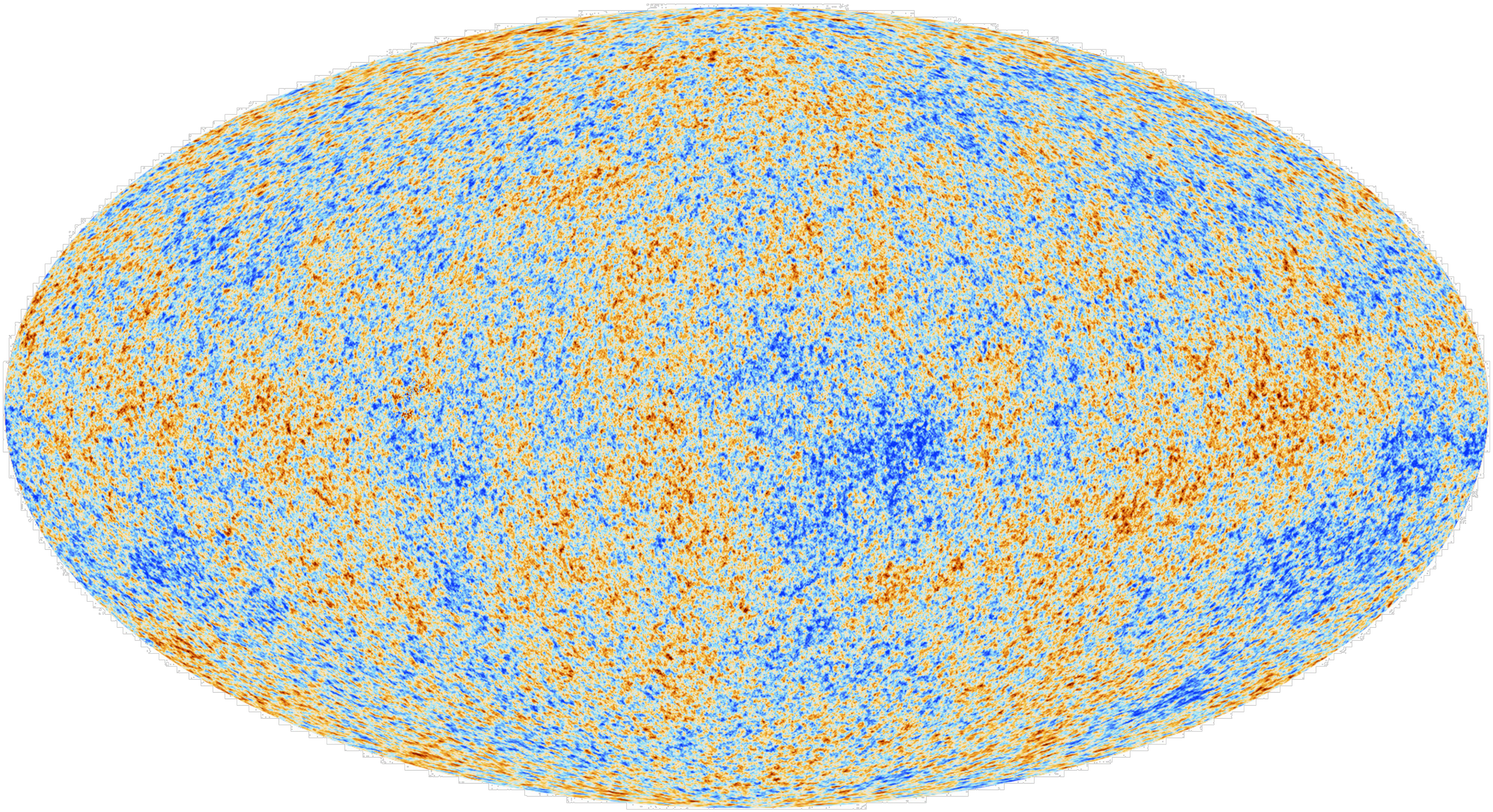
ACEC

AX CENTER *for* EXPERIMENTAL COSMOLOGY

UNIVERSITY OF CALIFORNIA SAN DIEGO

LET THERE BE LIGHT

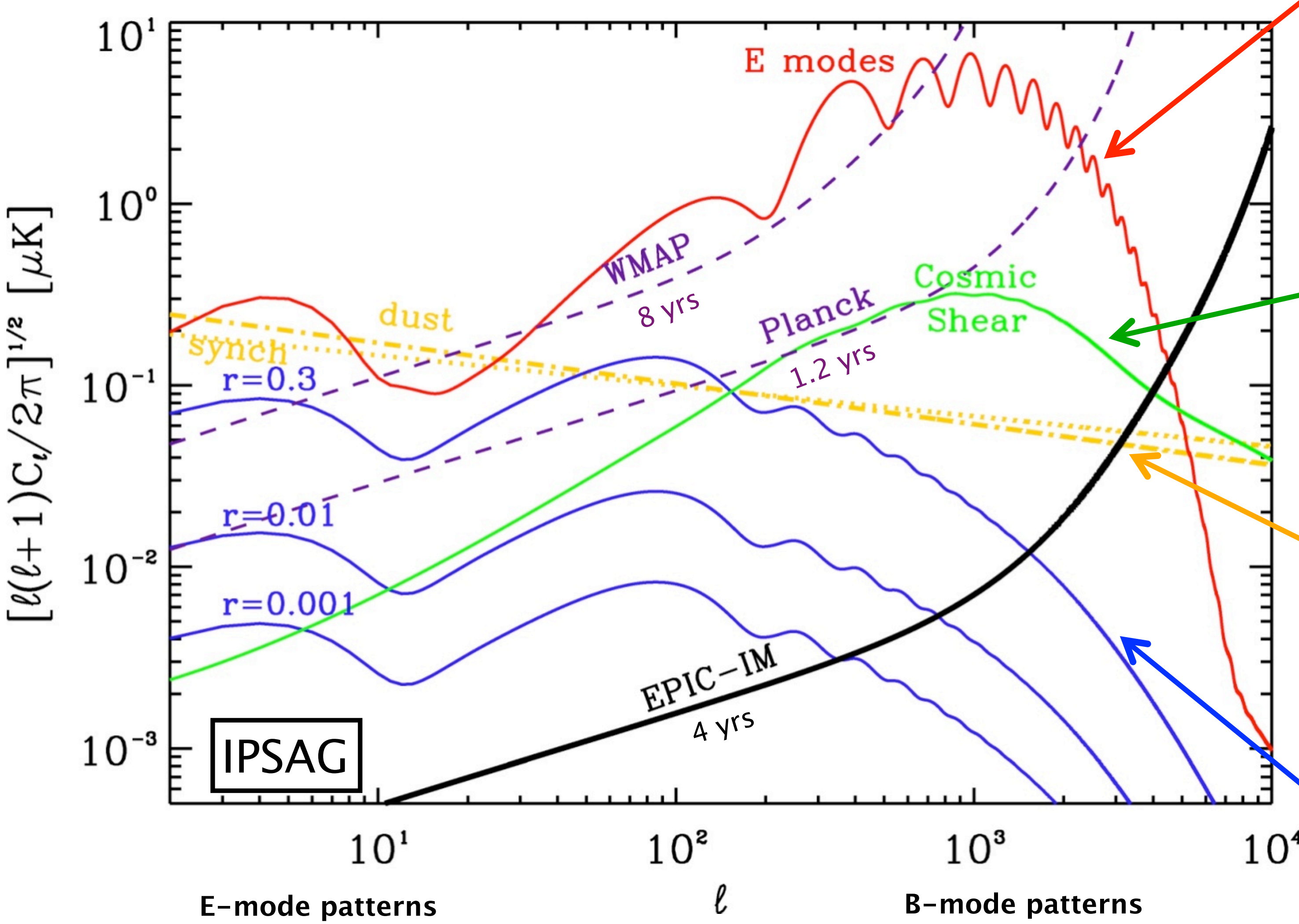
Planck Temperature Results!



Polarization data release in 2014

Focus for Next Decade: Polarization

CMB Polarization Angular Power Spectra



E-mode patterns

B-mode patterns

Scalar Perturbations
E-modes

- Precision cosmology
- Helium Abundance
- Departure from scale inv.
- Reionization history

Gravitational Lensing B-Modes
http://arxiv.org/abs/1307.5830

- Neutrino mass hierarchy
- Dark energy at z > 2

Galactic Magnetic Fields

- Star formation
- Large-scale B-fields

Inflationary Gravitational Waves
B-modes

- GUT energy scale
- Large field inflation
- n_t / r consistency test

Plus much more!

Focus on *Fun*damental Physics

Cosmic Microwave Background (CMB) polarization experiments can reveal:

Evidence for the universe's initial conditions via a detection of the CMB's large-scale B-mode polarization pattern, providing constraints on inflationary gravitational waves (at $E \sim 10^{16}$ GeV). Also, a form of indirect detection.

<u>Further Fundamental Physics:</u>

Neutrino masses

Helium abundance

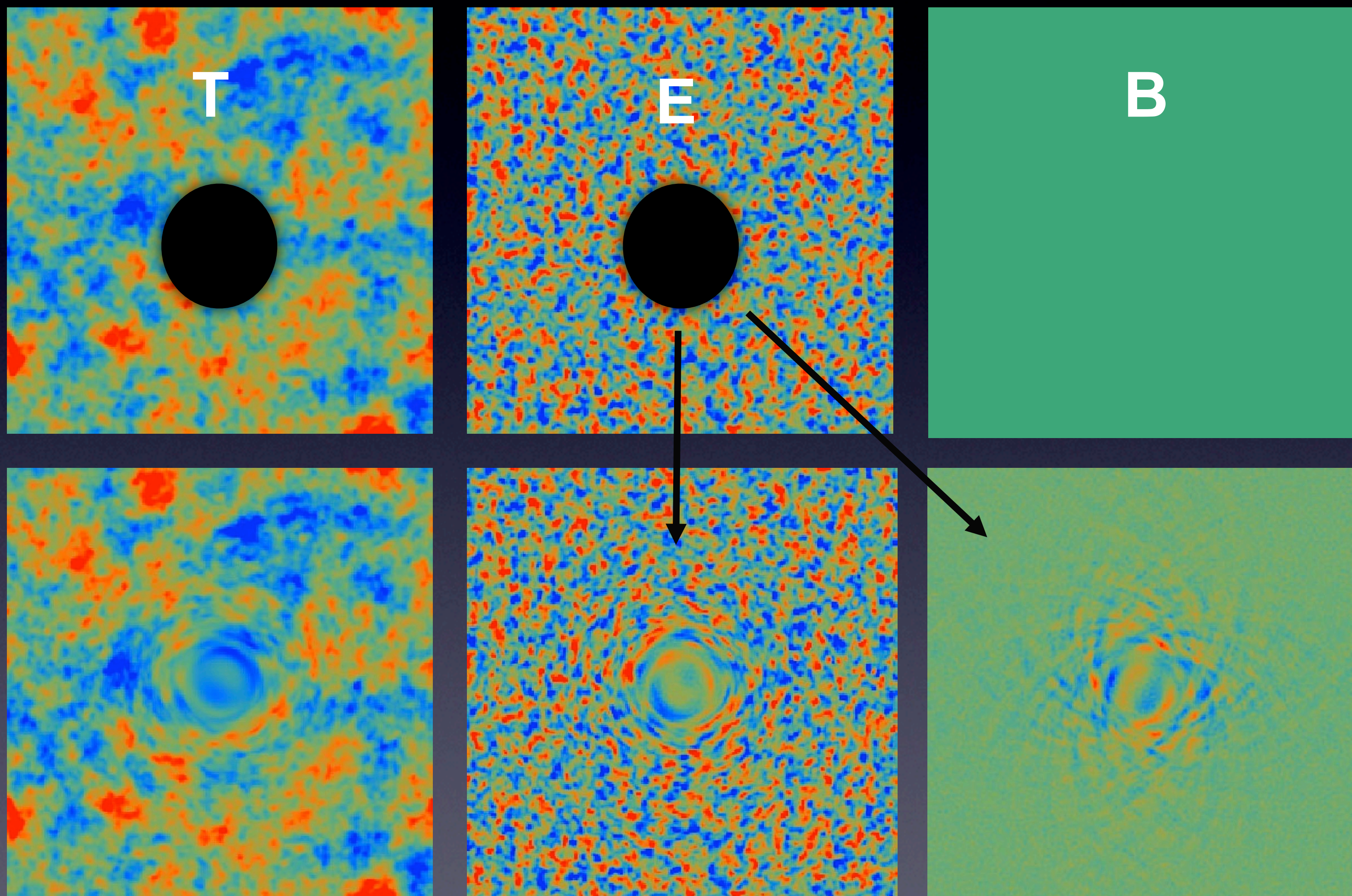
Neutrino chemical potentials

Interstellar magnetic fields

Primordial magnetic fields

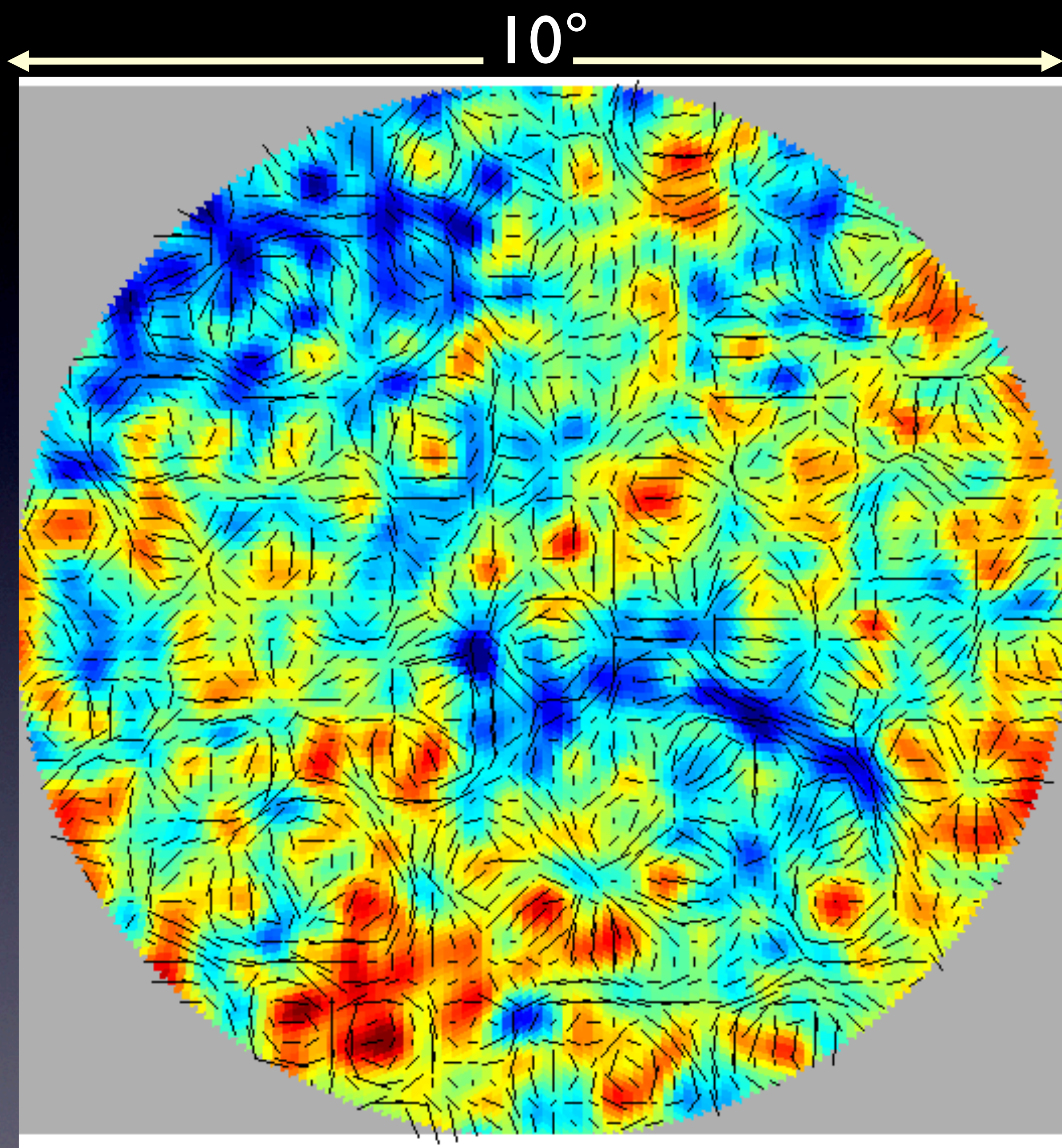
Exotic physics such as cosmic birefringence

“Is this Better or Worse?” Before & After Lensing Maps



Hu & Okamoto 2002

“Blink and You’ll Miss It!”



CMB Map

GWB: > 2° scales

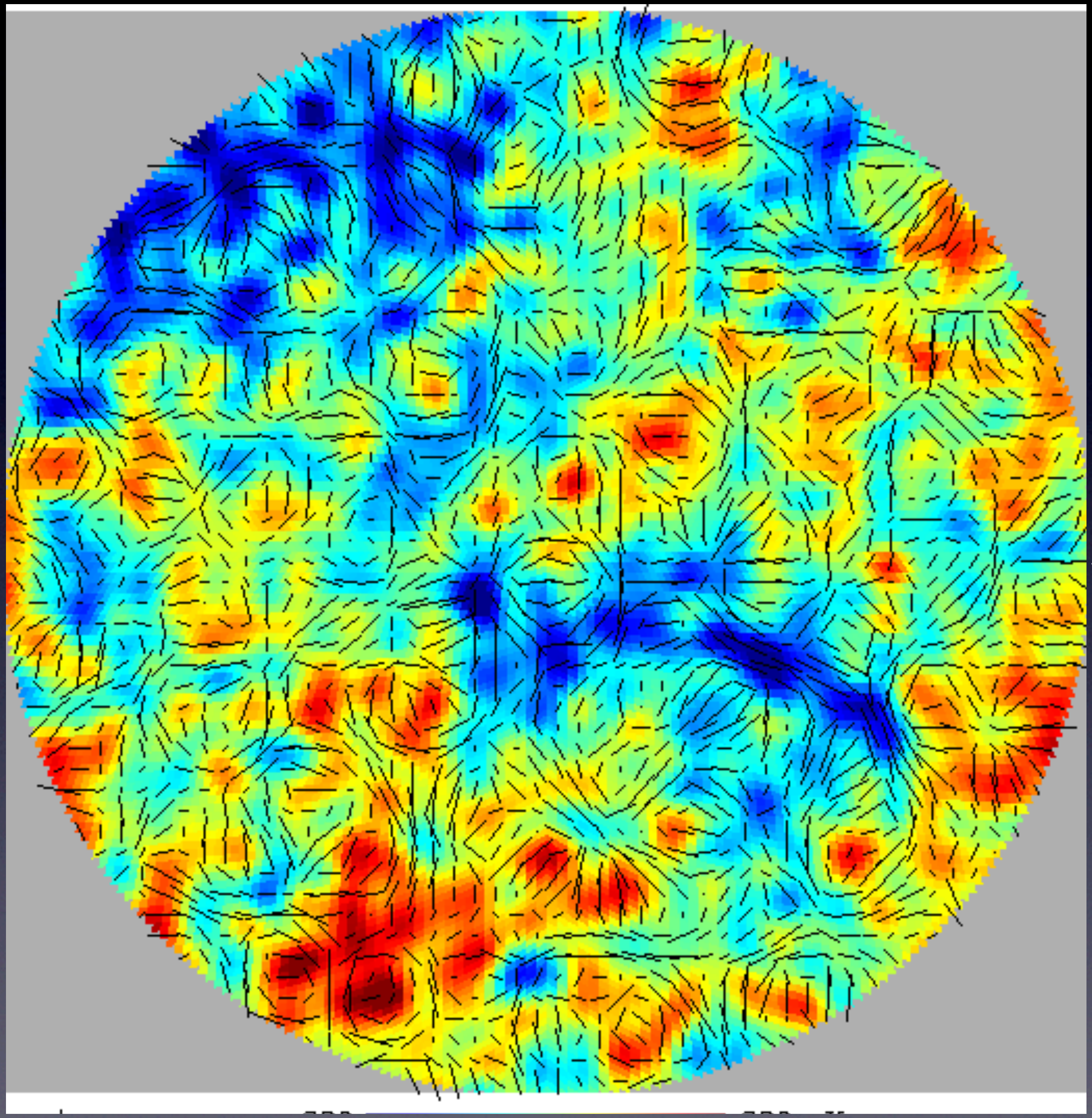
Lensing, m_ν < 0.1°

Helmholtz’s Thm:
“grad”: even parity
“curl”: odd parity

Without B-modes

"Blink and You'll Miss It!"

10°



CMB Map

GWB: > 2° scales

Lensing, m_ν < 0.1°

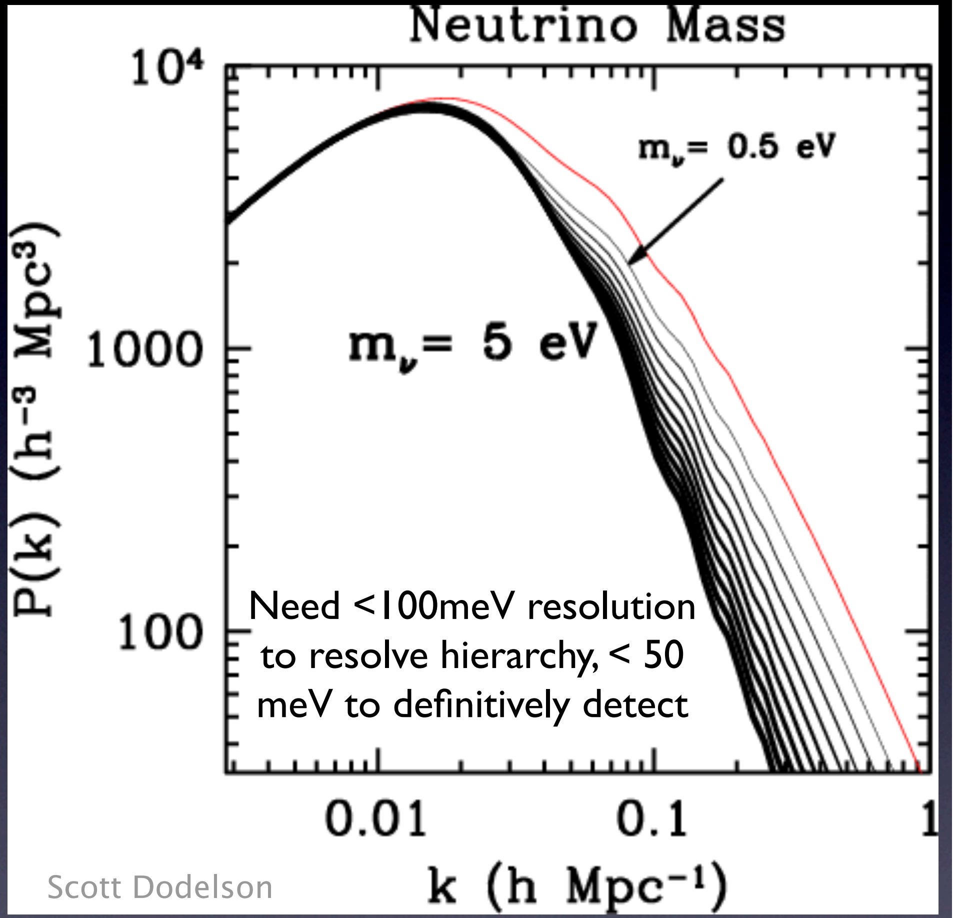
Helmholtz's Thm:
"grad": even parity
"curl": odd parity

Each photon is deflected by a few arcminutes but the structures responsible for lensing are coherent over ~3° scales.

With B-modes From Gravitational Lensing!

Neutrinos

- We now know there are only ~3 relativistic Fermions which are cosmologically relevant.
- At least one of the three neutrinos has mass (from neutrino oscillation experiments).
- Oscillation experiments are only sensitive to the square of the mass differences.
- Cosmological probes are sensitive to the sum of all three masses. The more massive the neutrinos are, the larger the suppression at small angular scales.



Neutrino mass and (possible) chemical potential affect structure formation.

Why is Polarization Sensitive to Lensing?

- B-mode polarization is *extremely* sensitive since it is a whole new signal (at small angular scales).
- EB correlations are *forbidden* without lensing, so EB is the *most sensitive* to the deflection angle (Hu & Okamoto,), and to neutrino physics: M_ν (Kaplinghat et al) and degeneracy, ξ (Shimon et al.) .
- As an additional bonus, EB is cleaner than TT.

Helium Abundance: As good as astrophysical bounds

- Galli et al. arXiv 1005:3808

High-\ell E-modes enter the horizon before the helium fully recombines

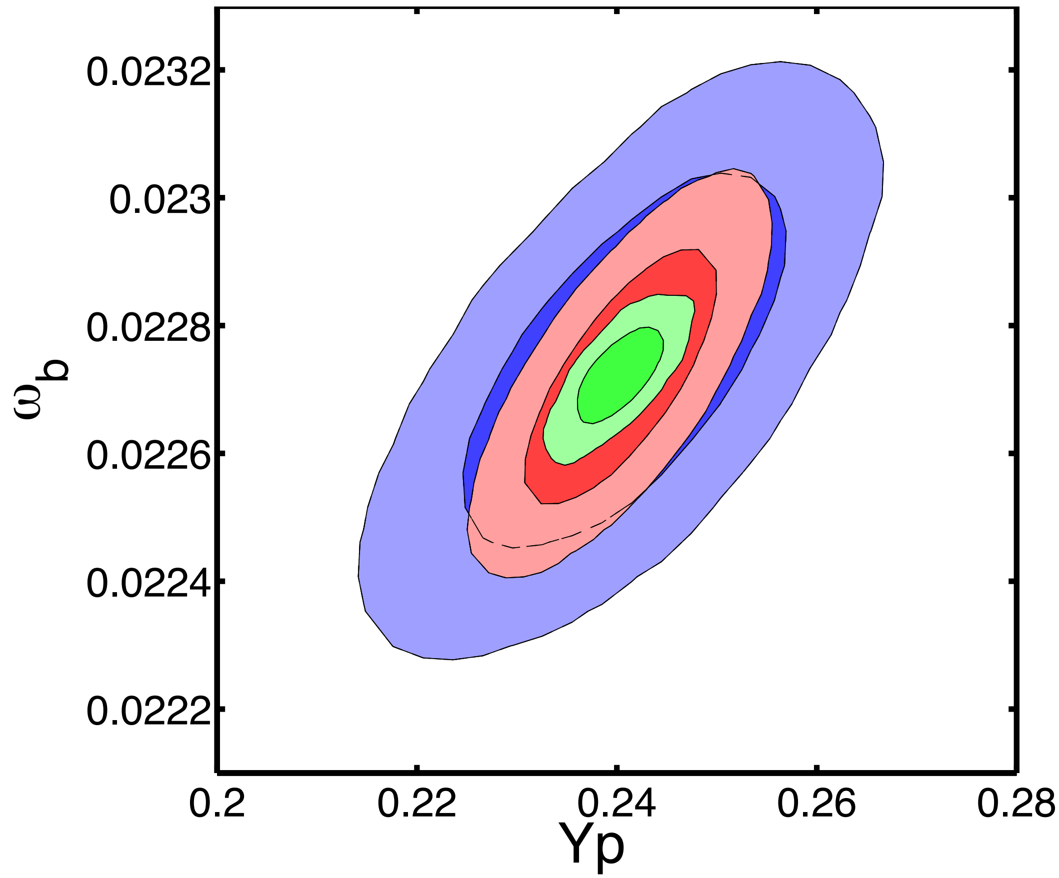


FIG. 8. 68% and 95% likelihood contour plots on the Y_{He} - ω_b plane for Planck (blue), Planck+ACTPol (red) and CMBPol (green).

Exotic: Primordial Magnetic field B

- Phase transitions- QCD, Electroweak, GUT
- Cosmic strings

$$\alpha = \frac{3}{16\pi^2 e}\lambda_0^2 \int \dot{\tau}\, \mathbf{B} \cdot d\mathbf{l}$$

Perhaps the magnetic fields we see in the structure around us, originated from seed magnetic fields imprinted in the "early universe"

Galaxies	B~ few μG,	~Kpc
Galaxy clusters	B~ 1-10 μG,	~10-100 Kpc
Objects at z~2	B~10 μG	

The physics responsible for generating the seed magnetic fields is largely unknown.

Name of the game

- We would like to detect the presence of primordial magnetic field (PMF) and
- would like to know the physics responsible for generating PMF

B $\xrightarrow{\text{Magnetic helicity and Magnetic flux are almost conserved during the evolution of the universe}}$ CMB

Yadav & Pogosian (2011)
Yadav, Shimon, & Keating (2012)

1. Magnetic anisotropic stress generates B-mode
2. Faraday rotation converting E to B

Exotic: Parity Violating Interactions

$$L \propto E^2 - B^2 \rightarrow E^2 - B^2 + g\vec{E} \cdot \vec{B}$$

Caroll & Field (1990)

Modified Lagrangian

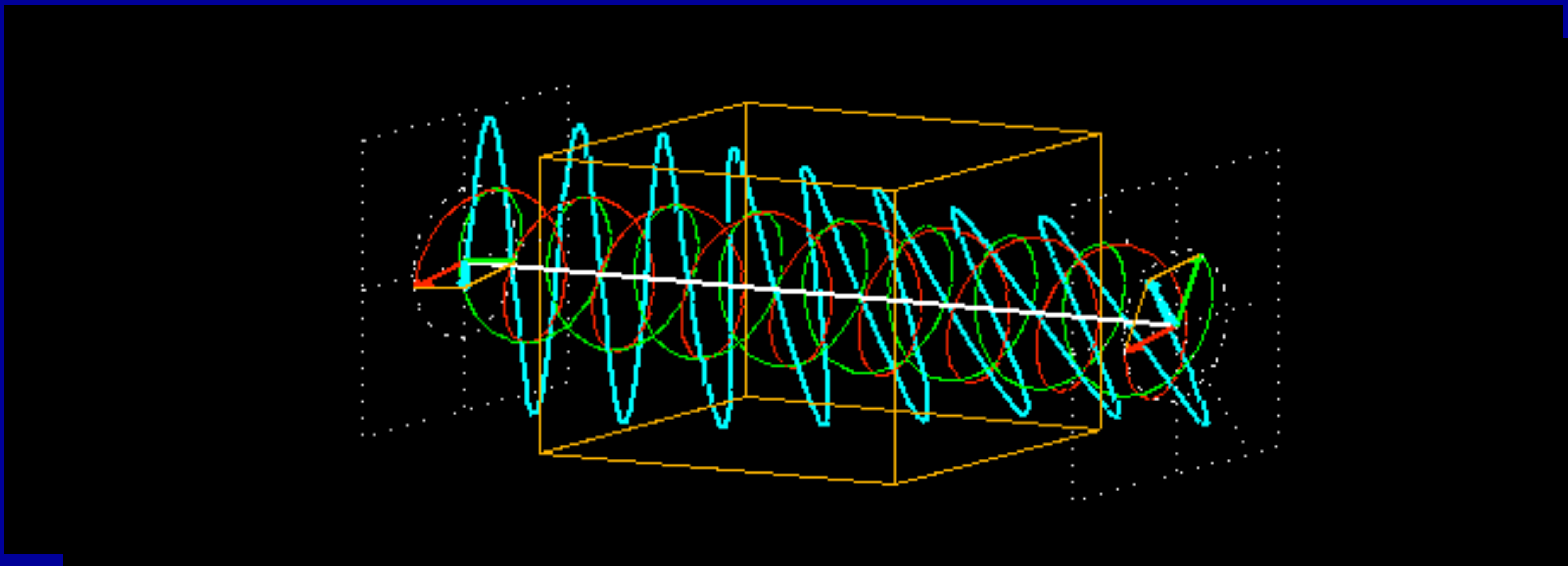
$$\omega^2 = k^2 \pm (4\pi g_\chi \dot{\chi})\, k$$

We have two different phase velocities; one for left-circular polarization, the other for right circular polarization.

The superposition of the two circular polarizations causes rotation of the plane of linear polarization!

Rotation of Polarization Plane

Cosmic Birefringence



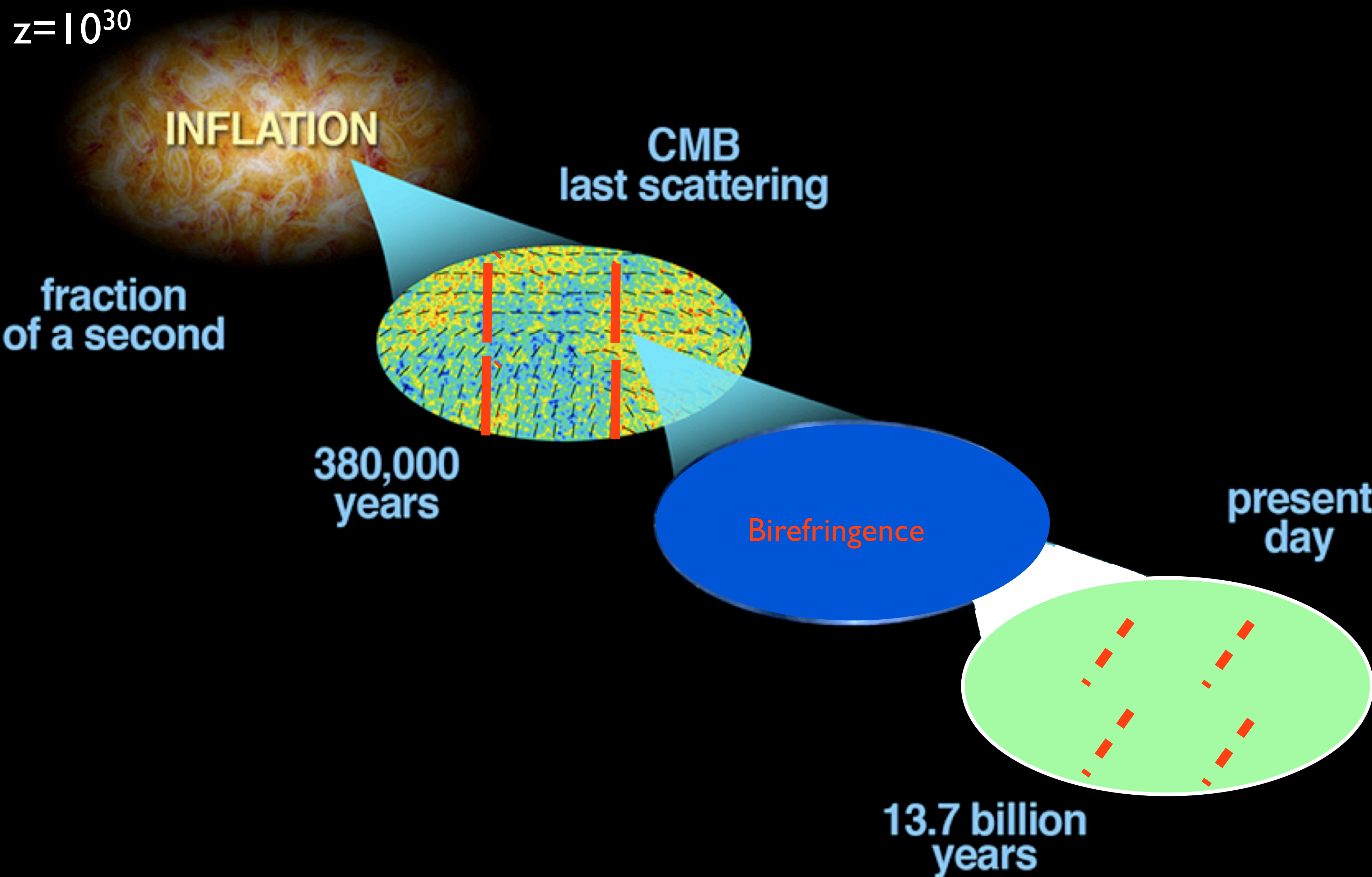
Rotation of the polarization plane $\Rightarrow$
mixing Q and U $\Rightarrow$
converting E $\rightarrow$ B $\Rightarrow$
inducing `forbidden' TB and EB

Miller, Shimon & BK (2009)

Shimon et al. 2009

Alexander & Yunes (2009)

Birefringence



August 2009

Xia et al. claim a *first* detection of CPT violation!?! Parameterized by Chern-Simons rotation angle α

Probing CPT Violation with CMB Polarization Measurements

Jun-Qing Xia[1], Hong Li[2,3], and Xinmin Zhang[2,3]
[1] *Scuola Internazionale Superiore di Studi Avanzati, Via Beirut 2-4, I-34014 Trieste, Italy*
[2] *Institute of High Energy Physics, Chinese Academy of Science, P. O. Box 918-4, Beijing 100049, P. R. China and*
[3] *Theoretical Physics Center for Science Facilities (TPCSF), Chinese Academy of Science, P. R. China*

The electrodynamics modified by the Chern-Simons term $\mathcal{L}_{cs} \sim p_\mu A_\nu \tilde{F}^{\mu\nu}$ with a non-vanishing p_μ violates the *Charge-Parity-Time Reversal* symmetry (CPT) and rotates the linear polarizations of the propagating *Cosmic Microwave Background* (CMB) photons. In this paper we measure the rotation angle $\Delta\alpha$ by performing a global analysis on the current CMB polarization measurements from the *five-year Wilkinson Microwave Anisotropy Probe* (WMAP5), *BOOMERanG 2003* (B03), BICEP and QUaD using a Markov Chain Monte Carlo method. We find that the results from WMAP5, B03 and BICEP all are consistent and their combination gives $\Delta\alpha = -2.62 \pm 0.87$ deg (68% *C.L.*), indicating a 3σ detection of the CPT violation for the first time. The QUaD data alone gives $\Delta\alpha = 0.59 \pm 0.42$ deg (68% *C.L.*) which has an opposite sign for the central value and smaller error bar compared to that obtained from WMAP5, B03 and BICEP. When combining all the polarization data together, we find $\Delta\alpha = 0.09 \pm 0.36$ deg (68% *C.L.*) which significantly improves the previous constraint on $\Delta\alpha$ and test the validity of the fundamental CPT symmetry at a higher level.

PACS numbers: 98.80.Es, 11.30.Cp, 11.30.Er

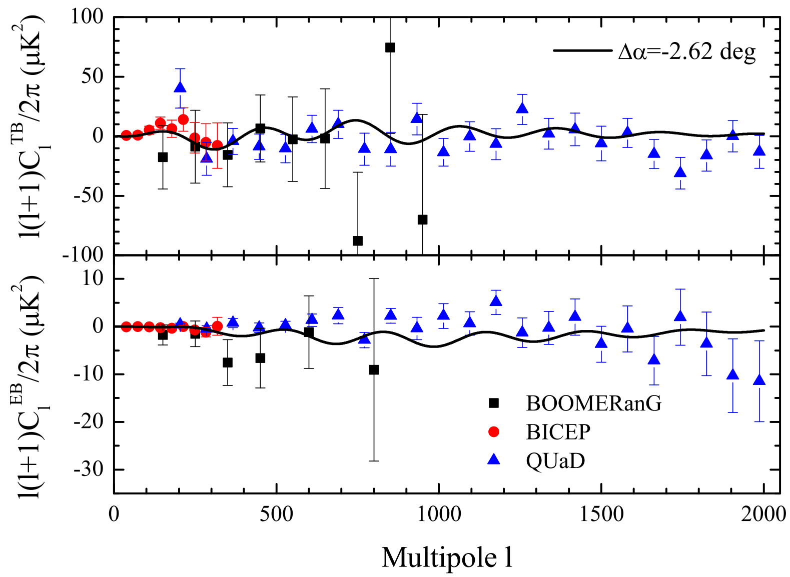


FIG. 1: The binned TB and EB spectra measured by the small-scale CMB experiments of BOOMERanG (black squares), BICEP (red circles) and QUaD (blue triangles). The black solid curves show the theoretical prediction of a model with $\Delta\alpha = -2.62$ deg.

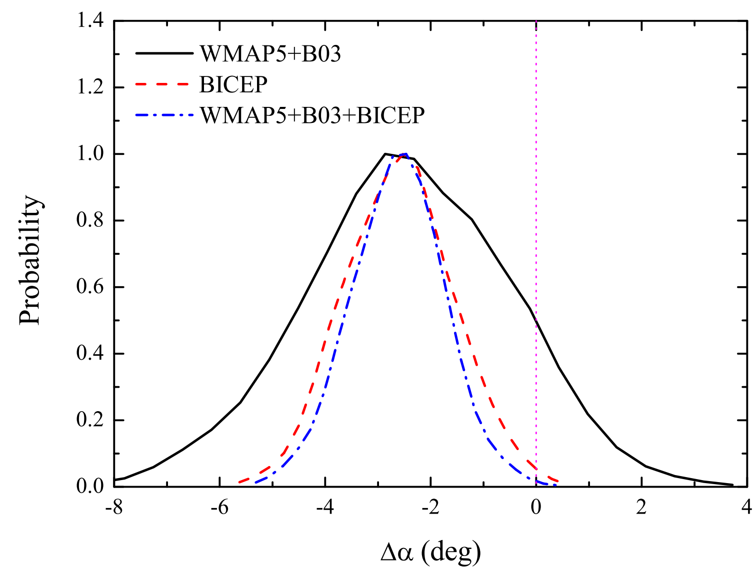


FIG. 2: One-dimensional posterior distributions of the rotation angle derived from various data combinations. The dotted vertical line illustrates the unrotated case ($\Delta\alpha = 0$) to guide eyes.

Crazy?

(1) **Birefringence and Lorentz-violation**: http://prd.aps.org/abstract/PRD/v41/i4/p1231_1
Jackiw, Field, & Carroll

(2) **Birefringence, Inflation and Matter-Antimatter asymmetry**: http://arxiv.org/pdf/hep-th/0403069.pdf ***Michael Peskin, Stephon Alexander***

(3) **Chern-Simons Inflation and Baryogenesis** http://arxiv.org/pdf/1107.0318.pdf
David Spergel, Stephon Alexander

(4) **Birefringence and Dark Energy**: http://arxiv.org/pdf/1104.1634.pdf
Marc Kamionkowski

(5) **Birefringence and Dark Matter detection** http://arxiv.org/pdf/astro-ph/0611684v3.pdf
Susan Gardner

(6) **Chern-Simons birefriencence and quantum gravity**: http://ccdb5fs.kek.jp/cgi-bin/img/allpdf?198402145 ***Edward Witten***

(7) Anomalous CMB polarization and gravitational chirality: http://lanl.arxiv.org/abs/0806.3082 ***Lee Smolin***

Current measurements of α

Method	CB rotation	Distance	Direction	
RG radio pol.	$\lvert\theta\rvert < 6^o$	$0.4 < z < 1.5$	all-sky (uniformity ass.)	
RG radio pol.	$\theta = -0.6^o \pm 1.5^o$	$\langle z \rangle = 0.78$	all-sky (uniformity ass.)	
RG UV pol.	$\theta = -1.4^o \pm 1.1^o$	$z = 0.811$	$RA: 176.37^o, Dec: 31.56^o$	
RG UV pol.	$\theta = -0.8^o \pm 2.2^o$	$\langle z \rangle = 2.80$	all-sky (uniformity ass.)	
RG UV pol.	$\langle \theta^2 \rangle \leq (3.7^o)^2$	$\langle z \rangle = 2.80$	all-sky (stoch. var.)	
WMAP7	33+41+61	$2-23$	$-3.8 \pm 5.2 \pm 1.5$	[1]
WMAP7	**41+61+94**	**24-800**	$\mathbf{-0.9 \pm 1.4 \pm 1.5}$	**[1]**
WMAP7	33+41+61+94 [1]	$2-800$	$-1.1 \pm 1.4 \pm 1.5$	[1]
WMAP7	33+41+61	$2-23$	$-3.0^{+2.6}_{-2.5}$ [2]	[18]
WMAP7	33+41+61	$2-47$	-1.6 ± 1.7	[18]
WMAP7	33+41+61	$2-30$	$-4.2^{+1.9}_{-3.1}{}^{+10.2}_{-7.5}$	[19]
WMAP7	33+41+61	$2-800$	$-1.3^{+0.6}_{-0.7}{}^{+2.3}_{-2.3}$	[19]
BOOM03	**145**	**150-1000**	$\mathbf{-4.3 \pm 4.1}$ [3]	**[20]**
QUAD	**100**	**200-2000**	$\mathbf{-1.89 \pm 2.24 \pm 0.5}$	**[21]**
QUAD	**150**	**200-2000**	$\mathbf{0.83 \pm 0.94 \pm 0.5}$	**[21]**
QUAD	100+150	$200-2000$	$0.64 \pm 0.5 \pm 0.5$	[22]
BICEP	**100+150**	**21-335**	$\mathbf{-2.60 \pm 1.02 \pm 0.7}$	**[13]** [4]

http://arxiv.org/pdf/1211.3321v2.pdf

Beam Systematics Impact on Cosmological Birefringence

- Intensity leakage to polarization: T→E,B

$$B \propto \omega T, \quad \omega << 1$$

$$C_l^{BB} \propto \omega^2 C_l^{TT}$$

$$C_l^{TB} \propto \omega C_l^{TT}$$

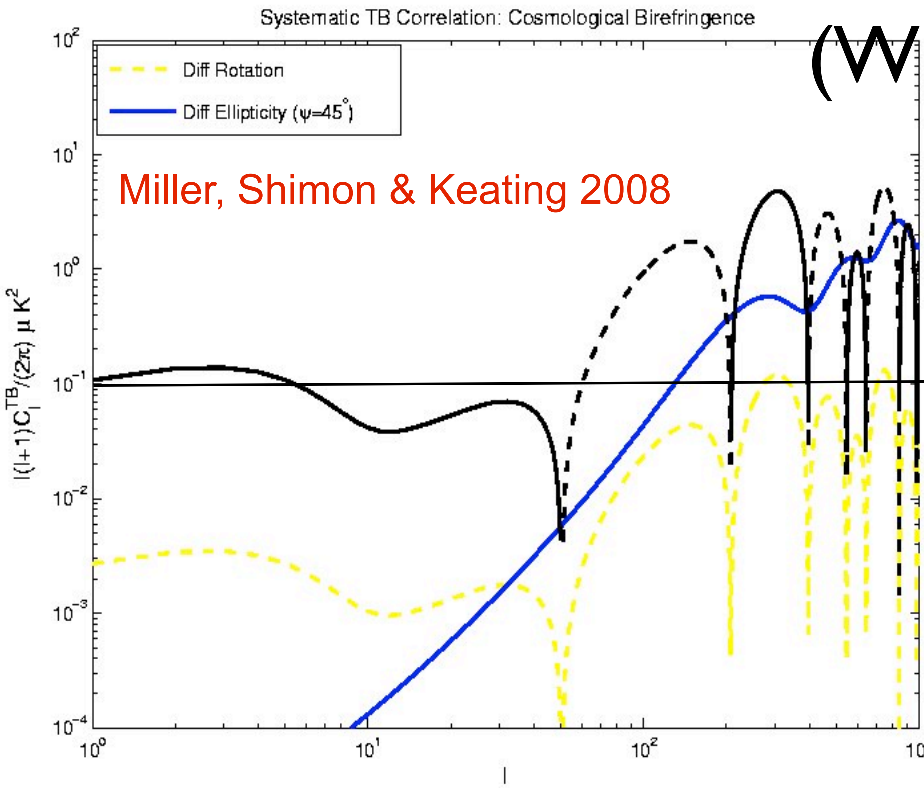
Therefore, keeping C_l^{BB} low does not necessarily guarantee low C_l^{TB}

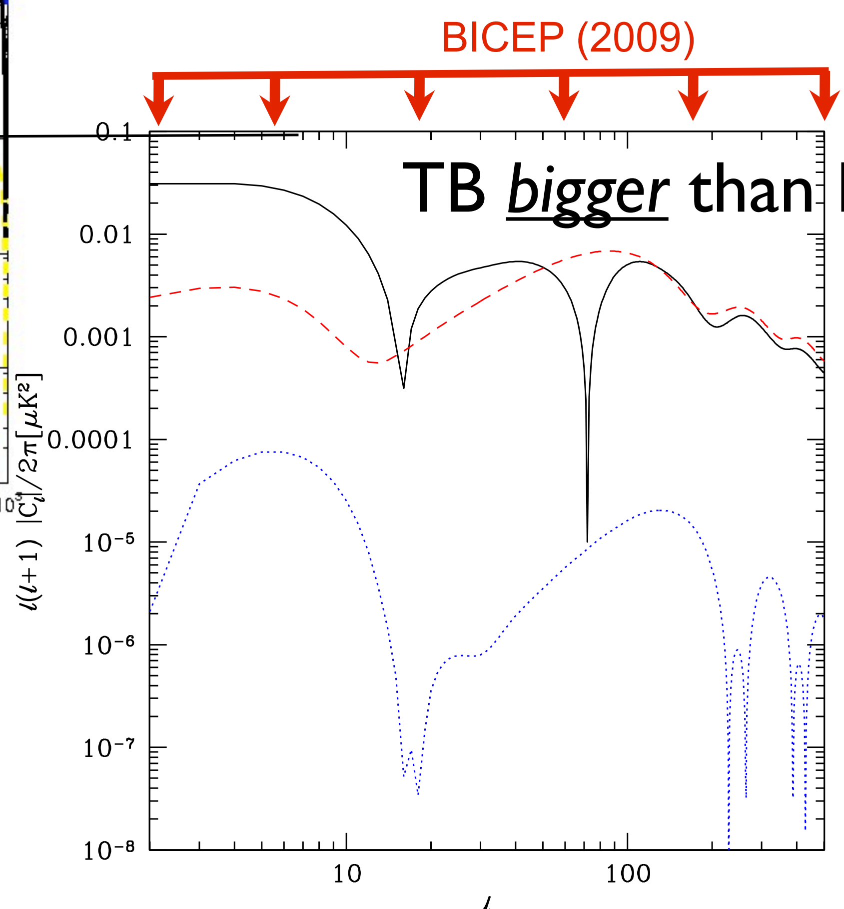
But, can use to "self-calibrate" polarization angle (Keating, Shimon & Yadav (2013)

From Miller et al. 2009

Contaldi, Magueijo & Smolin (2008)

(Why not let gravity violate parity?)





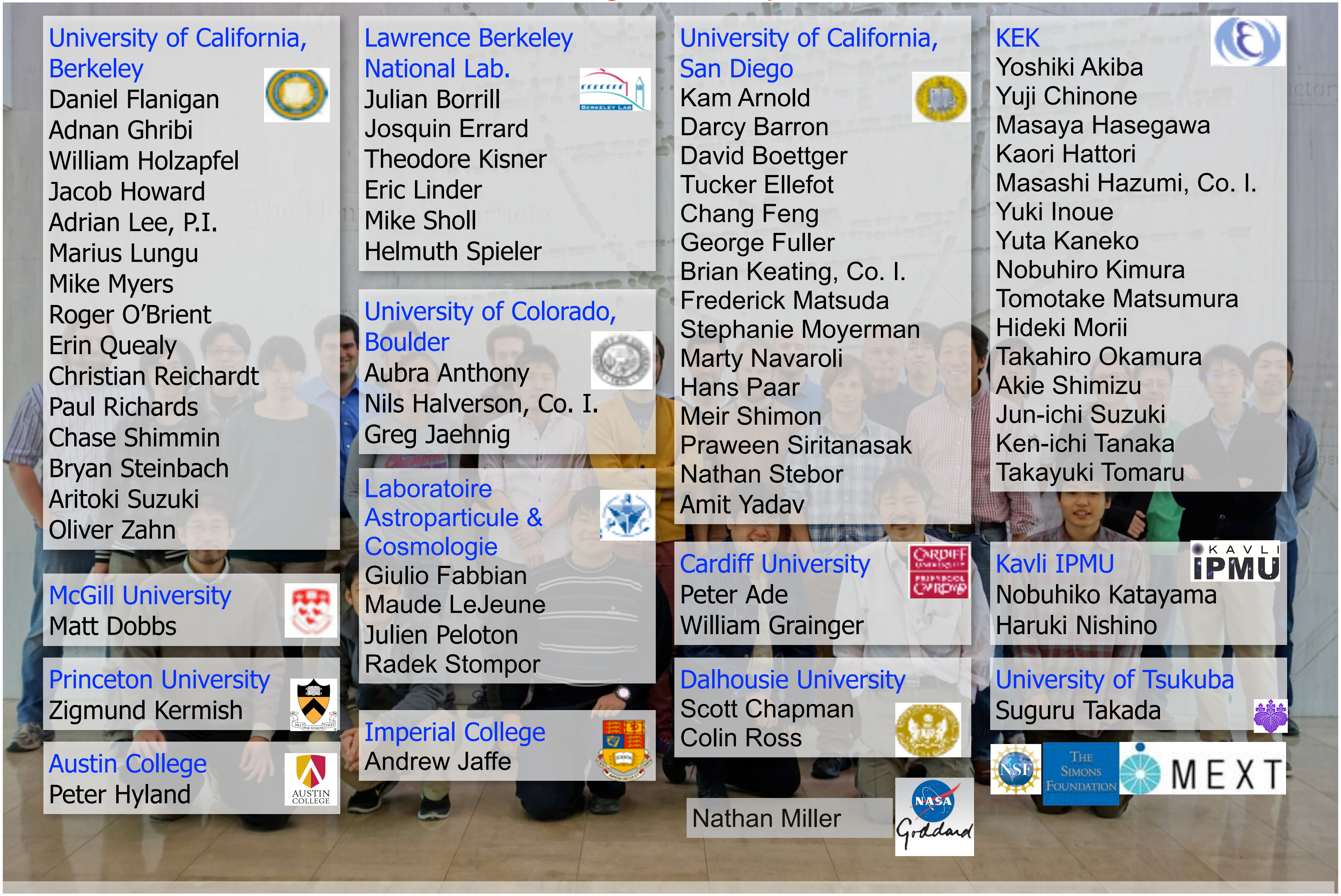
Systematics should be manageable for TB!

FIG. 1: Tensor contribution to the TB (solid, black), BB (dashed, red), and EB (dotted, blue) spectra for a standard ΛCDM model with tensor to scalar ratio $r = 0.1$ and chirality parameter $\gamma = 10$.

The POLARBEAR Experiment

POLARBEAR Collaboration

POLARBEAR Collaboration Meeting @ KEK, Japan, Mar. 24-28, 2013



University of California, Berkeley
Daniel Flanigan
Adnan Ghribi
William Holzapfel
Jacob Howard
Adrian Lee, P.I.
Marius Lungu
Mike Myers
Roger O'Brient
Erin Quealy
Christian Reichardt
Paul Richards
Chase Shimmin
Bryan Steinbach
Aritoki Suzuki
Oliver Zahn

McGill University
Matt Dobbs

Princeton University
Zigmund Kermish

Austin College
Peter Hyland

Lawrence Berkeley National Lab.
Julian Borrill
Josquin Errard
Theodore Kisner
Eric Linder
Mike Sholl
Helmuth Spieler

University of Colorado, Boulder
Aubra Anthony
Nils Halverson, Co. I.
Greg Jaehnig

Laboratoire Astroparticule & Cosmologie
Giulio Fabbian
Maude LeJeune
Julien Peloton
Radek Stompor

Imperial College
Andrew Jaffe

University of California, San Diego
Kam Arnold
Darcy Barron
David Boettger
Tucker Ellefot
Chang Feng
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Brian Keating, Co. I.
Frederick Matsuda
Stephanie Moyerman
Marty Navaroli
Hans Paar
Meir Shimon
Praween Siritanasak
Nathan Stebor
Amit Yadav

Cardiff University
Peter Ade
William Grainger

Dalhousie University
Scott Chapman
Colin Ross

Nathan Miller

KEK
Yoshiki Akiba
Yuji Chinone
Masaya Hasegawa
Kaori Hattori
Masashi Hazumi, Co. I.
Yuki Inoue
Yuta Kaneko
Nobuhiro Kimura
Tomotake Matsumura
Hideki Morii
Takahiro Okamura
Akie Shimizu
Jun-ichi Suzuki
Ken-ichi Tanaka
Takayuki Tomaru

Kavli IPMU
Nobuhiko Katayama
Haruki Nishino

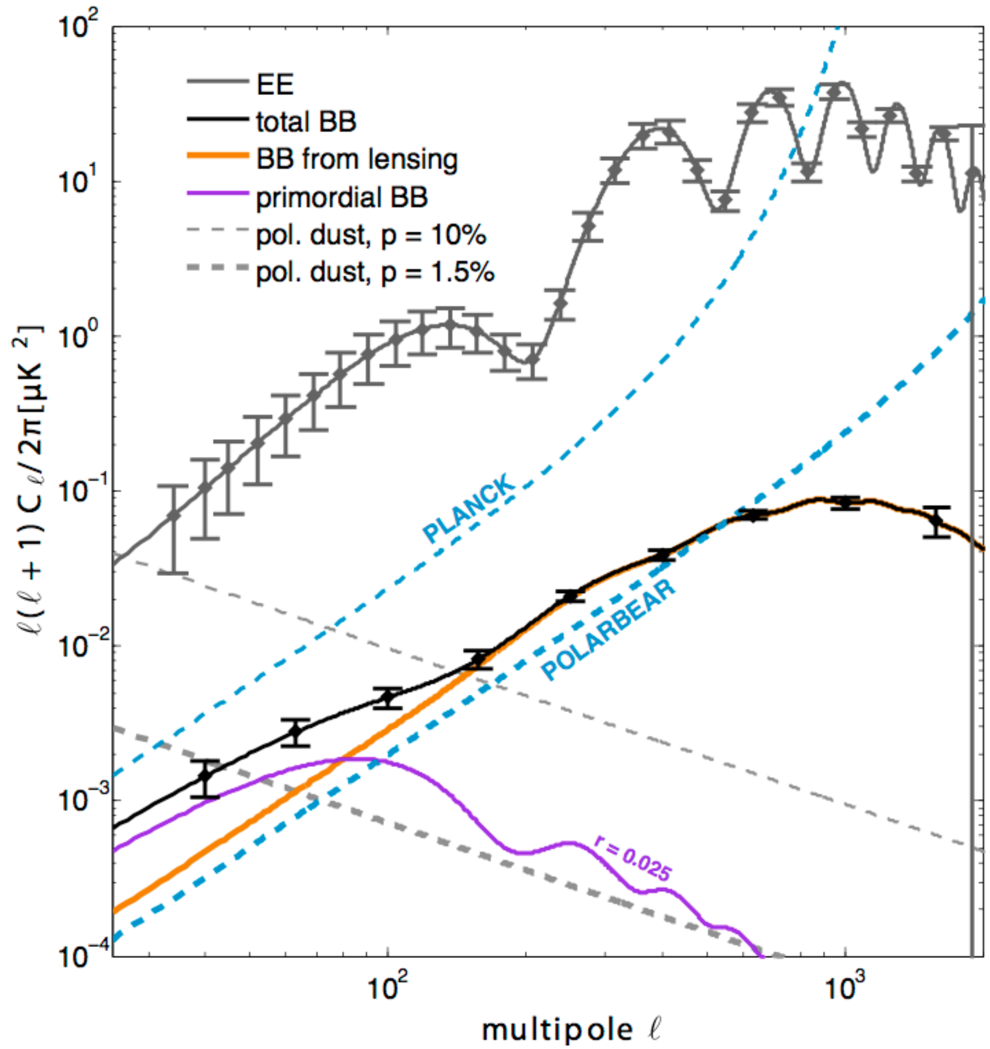
University of Tsukuba
Suguru Takada

International Collaboration from 5 countries, 14 institutes, ~70 members

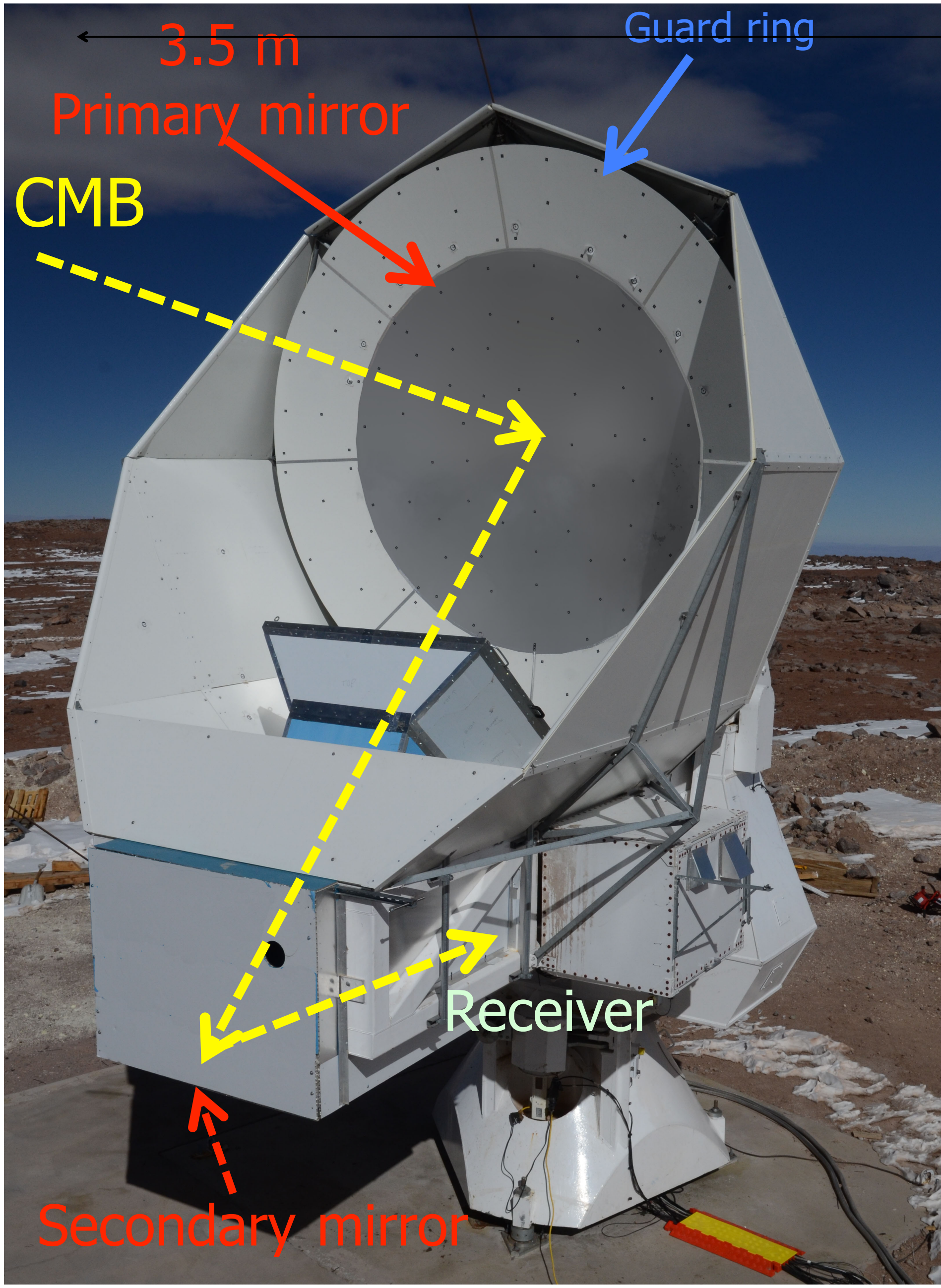
Goals of POLARBEAR

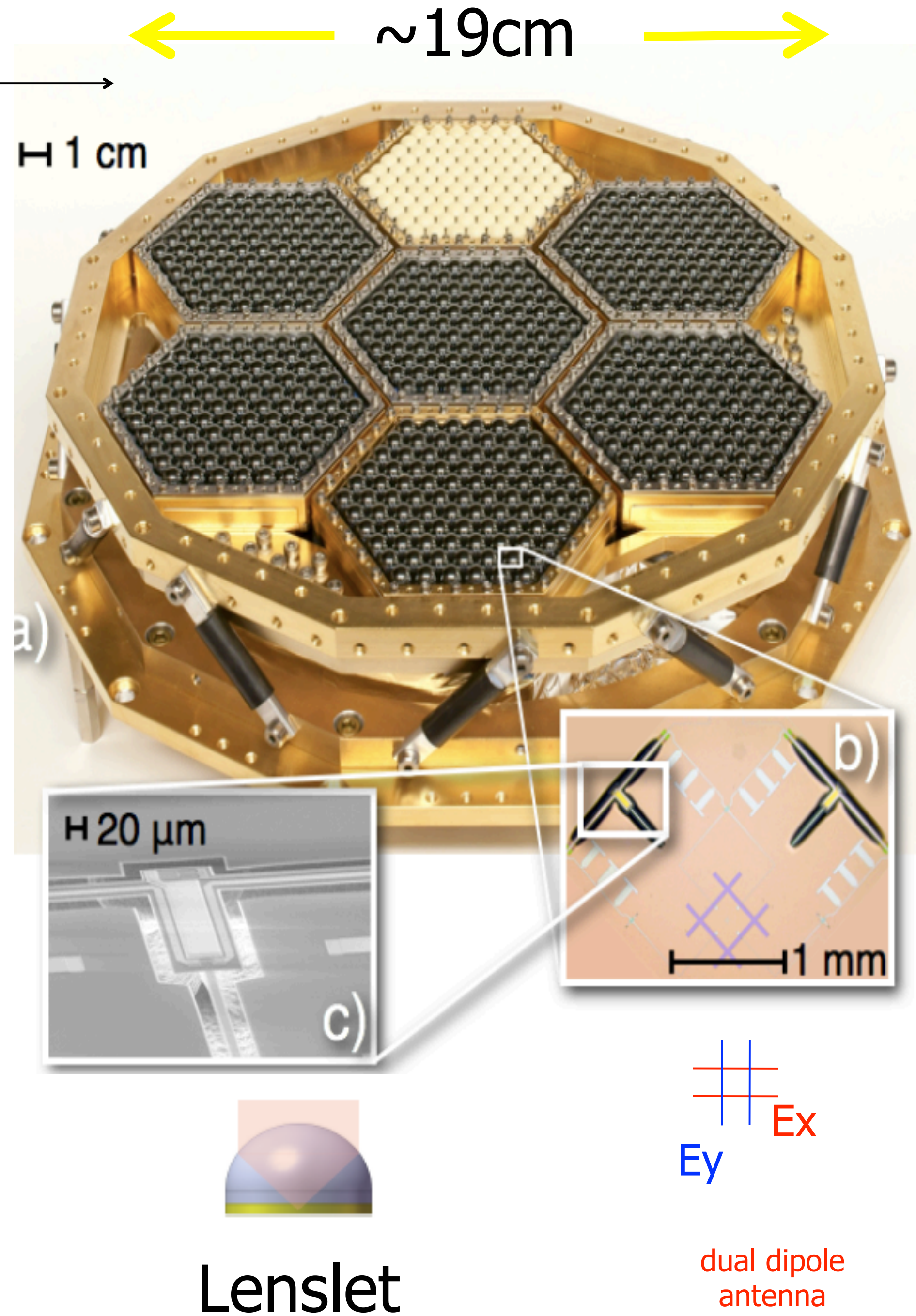
- Search for inflationary B-modes to r=0.025 (95% CL) & detect gravitational lensing B-modes.
- Set first constraints on neutrino parameters from CMB polarization alone.
- Look for “beyond the standard model”, such as Cosmic Birefringence, primordial magnetic fields.

2yrs observation

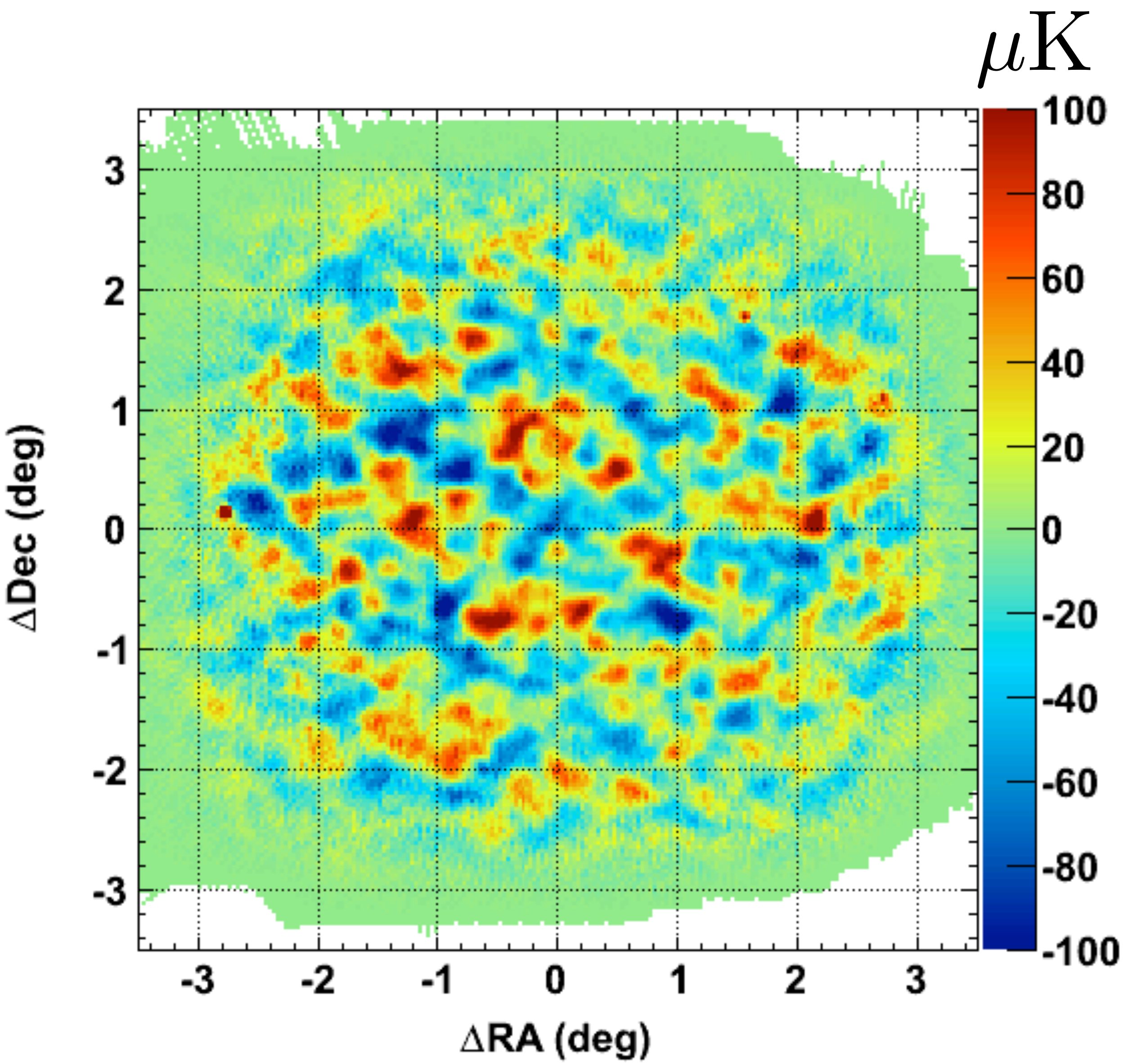


Huan Tran Telescope (HTT) @ the James Ax Observatory

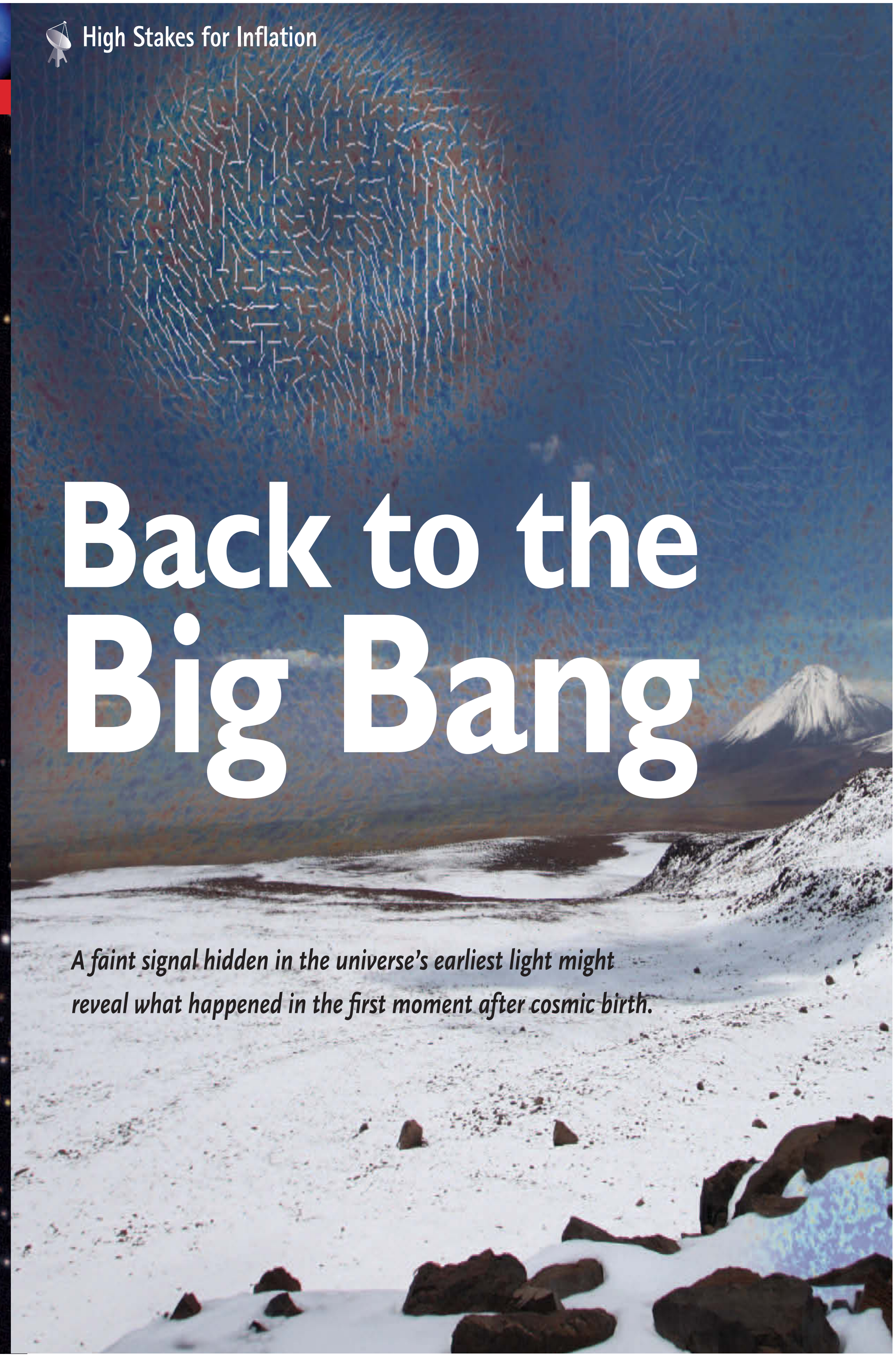




Temperature Anisotropy Map



- Roughly 10 times deeper than Planck (@143GHz)
- Our analysis pipeline works well
- One of three patches



High Stakes for Inflation

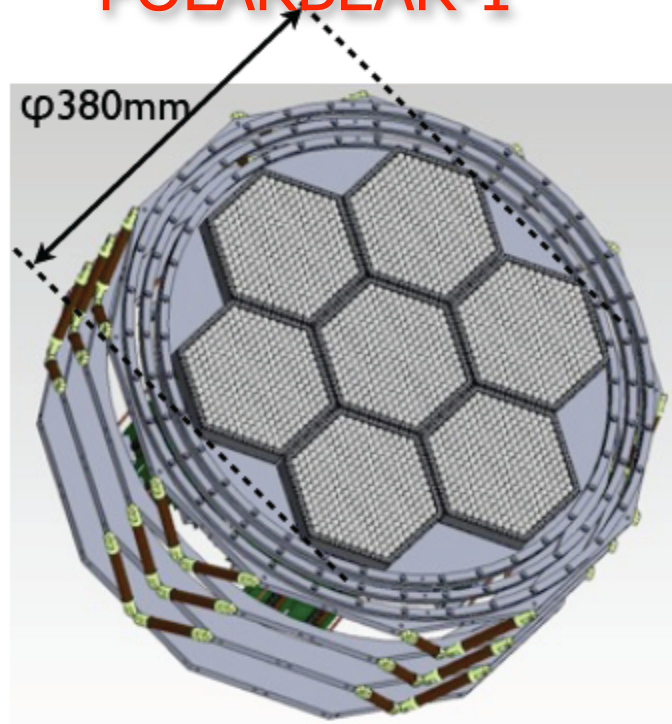
Back to the Big Bang

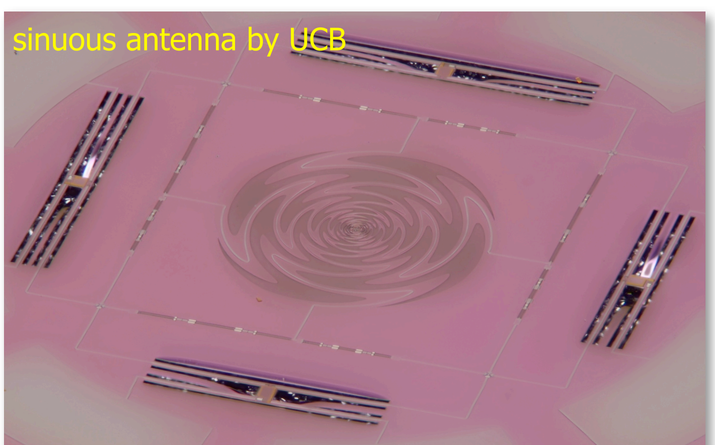
A faint signal hidden in the universe's earliest light might reveal what happened in the first moment after cosmic birth.

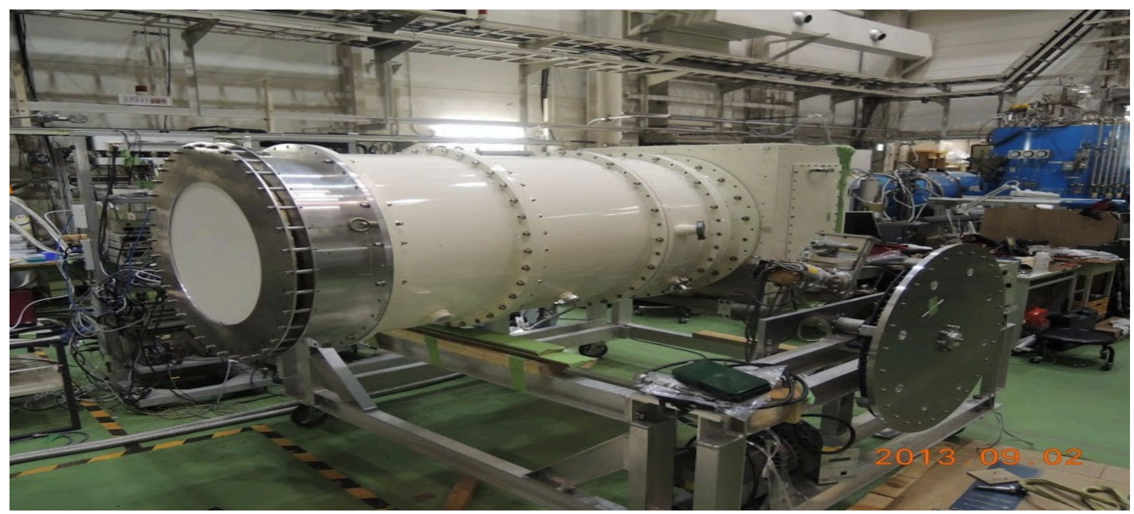
POLARBEAR Roadmap

- POLARBEAR-2 (2014+)
  - 3.5′ beam & 7,588 bolometers
  - 90/150 GHz dual-band pixels
  - r ~ 0.01 (95% C.L.)
  - 90 meV neutrino mass (68% C.L.)
  - “Stage 3”

6 times more than POLARBEAR-1







Simons Array (2016)

Brian Keating (PI), Adrian Lee (co-PI)
Kam Arnold (PM)

80% of … ble from Chile

- 3 x Te … 3 … eivers (UCSD & UCB)
  - > 22,(…
- 90/15(… pixels

Postdoc and Fab Tech Positions at UCSD & UCB

Hardware: funded by Simons Foundation

POLARBEAR Roadmap

- current POLARBEAR (POLARBEAR-1)
  - 3.5′ beam & 1,274 bolometers
  - Array NET = 21 uK√s
  - r ~ 0.025 (95% C.L.)
- POLARBEAR-2
  - 3.5′ beam & 7,588 bolometers
  - 90/150 GHz dual-band pixels
  - r ~ 0.01 (95% C.L.)
- Simons Array
  - 3 Telescopes, > 22,000 bolometers)
  - 90/150/220 GHz dual-band pixels
  - r ~ 0.007 (95% CL)
  - Scalable: more telescopes or 3-band pixels

2012

2014

2016